# *INTEGRAL* THREE YEARS LATER

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The ESA *INTErnational Gamma-Ray Astrophyisics Laboratory* (*INTEGRAL*) is composed of two main instruments (IBIS and SPI) for the $\gamma-$ray astrophysics (20 keV – 10 MeV), plus two monitors (JEM-X and OMC) for X-ray and optical counterparts. It was launched on October 17$^{\rm th}$, 2002, from the Baikonur cosmodrome (Kazakhstan) and it will be active at least up to 2008. A selection of its main scientific contributions obtained to date are presented.

## 1. Introduction

The *INTE*rnational *G*amma-*R*ay *A*strophysics *L*aboratory (*INTEGRAL*)[1] is an observatory of the *European Space Agency* (ESA). Launched in 2002, with a nominal duration of 2 years, it has already been extended up to 2008. *INTEGRAL* has been built by the ESA member states with the participation of United States, Russia, Czech Republic, and Poland. *Alenia Spazio* (Italy) has been appointed by ESA as prime contractor for the design, integration, and testing of the satellite[2]. The *Mission Operation Centre* (MOC) at Darmstadt (Germany) is continuously in touch with the satellite through two ground stations, one of ESA located at Redu (Belgium) and the other of NASA at Goldstone (USA). The *INTEGRAL Science Operation Centre* (ISOC) was initially at ESA ESTEC (The Netherlands), and in 2005 moved to ESAC in Spain[3]. The *INTEGRAL Science Data Centre* (ISDC) is located at Versoix in Switzerland[4].

Two are the main instruments on board: SPI (*SPectrometer on Integral*)[6] and IBIS (*Imager on Board Integral Satellite*)[5]. The first is dedicated to high-energy resolution spectroscopy (2.5 keV at 1.3 MeV) and it is composed of 19 Germanium detectors operating in the 20 keV – 8 MeV energy range. The second is an imaging telescope optimized for high-resolution ($12'$) wide field of view (FOV, $29^\circ \times 29^\circ$) point source reconstruction with moderate energy resolution (8% at 100 keV and 10% at 1 MeV). IBIS is

composed of two layers: ISGRI (*INTEGRAL Soft Gamma-Ray Imager*[7]), a $128 \times 128$ pixels CdTe detector organized in 8 modules operating in the 20 keV – 1 MeV energy range, and PICsIT (*Pixellated Imaging CaeSium Iodide Telescope*[8]), a $64 \times 64$ pixels CsI detector organized in 8 modules operating in the 175 keV – 10 MeV energy range.

These instruments are complemented by two monitors: JEM-X (*Joint European Monitor X-rays*[9]), operating in the $3 - 35$ keV energy band with angular resolution of $3'$, and OMC (*Optical Monitor Camera*[10]), for optical study in the Johnson V band with magnitude limit 18.

IBIS, SPI, and JEM-X detectors are all coupled with tungsten coded-masks: SPI and JEM-X make use of a hexagonal uniformly redundant array (HURA), while the IBIS mask is a modified uniformly redundant array (MURA). Specific mathematical operations (deconvolution) are needed to obtain images, spectra, and lightcurves, and are described in Goldwurm et al.[11] and Gros et al.[12] for IBIS, in Skinner & Connell[13] and Strong[14] for SPI, and in Westergaard et al.[15] for JEM-X.

Since *INTEGRAL* is an observatory, most of its time is dedicated to the astronomical community, through annual announcements of opportunity (AO). However, part of the observing time is reserved to the Instrument Teams and constitutes the Core Programme (CP). The CP covered 35% of the total observing time during the first year and decreased to 30% in the second year, and to 25% in the third year. The scientific topics of the CP are focused on regular scans of the Galactic plane and deep exposures on the central radian of the Milky Way and other specific regions (Norma and Scutum Arms, Vela and Virgo regions). One year after the observation, all the data become public[a].

## 2. Science

The main scientific topics addressed by *INTEGRAL* satellite observations can be divided into: *Compact objects:* neutron stars, anomalous X-ray pulsars, soft-gamma repeaters, black holes; *The Milky Way:* the Galactic Centre and Sgr A*, diffuse and line emission; *Stellar nucleosynthesis:* hydrostatic (AGB, Wolf-Rayet) and explosive (SN, Novae); *Extragalactic astrophysics:* active galactic nuclei (seyferts, blazars, radiogalaxies), clusters of galaxies, gamma-ray bursts (GRB); *Identification of high-energy sources:* EGRET unidentified sources, new discoveries; *Unexpected discoveries*.

[a] For more details, see the documentation enclosed to each Announcement of Opportunity available at `http://integral.esac.esa.int/`.

In the following we shortly present a selection of the most important results obtained with *INTEGRAL*, with apologies to those about which we cannot report, because of space limitations.

### 2.1. *The Galactic Centre*

One of the most important results was obtained thanks to the unprecedented angular resolution of IBIS/ISGRI. The problem was the understanding of the excess of diffuse emission in the Galactic centre: indeed, previous missions found a strong $\gamma-$ray diffuse emission toward the centre of the Milky Way, that was thought to be originated from the interaction of cosmic-rays with interstellar medium (see Pohl[16] for a review). However, this model cannot explain excesses in the spectrum around 100 keV and above 1 GeV. *INTEGRAL* performed a deep exposure (1.5 Ms) toward the central radian of the Galaxy, and demonstrated that the excess was due to point sources not resolved by previous experiments[17].

Again IBIS/ISGRI performed an accurate study of Sgr A* and found a new hard X-ray source IGR J1745.6 $-$ 2901, consistent with the Galactic Centre within $\approx 1'$, so that the association with Sgr A* is not conclusive[18]. On the other hand, the flux of IGR J1745.6$-$2901 is not consistent with the diffuse and point sources emission within $10'$ extrapolated from *Chandra* and *XMM-Newton* observations. These two X-ray satellites have observed some transients in the ISGRI error box, but these are too weak and soft to be associated with the hard X-ray source.

Another newly discovered *INTEGRAL* source, namely IGR J17475 $-$ 2822, has been associated with the giant molecular cloud Sgr B2[19]. To explain how a molecular cloud could emit hard X-rays, it has been suggested that the radiation could be the result of a past activity of Sgr A* ($\approx 300-400$ years ago, when it behaved as an active galactic nucleus), that was Compton scattered and reprocessed by Sgr B2[19].

The spectrometer SPI focused on the electron-positron annihilation line (511 keV) and found a significant ($\approx 50\sigma$) emission from the Galactic bulge[20]. This emission region is centered on the Galactic centre, is symmetric, and is about $8^\circ$ wide. There is no evidence of the positive latitude enhancement found by OSSE[21] and the emission along the Galactic disk is constrained with low significance ($\approx 4\sigma$).

### 2.2. *Compact objects*

Thanks to its characteristics, *INTEGRAL* can give important contribution mainly in the astrophysics of compact objects. Indeed, with a sensitivity of about $(0.8-1)\times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ in the $20-40$ keV energy band ($10-15$ mCrab) for a $3\sigma$ detection in 2 ks, the IBIS/ISGRI detector is efficiently used to monitor the X-ray binaries population in the Milky Way with the regular scans of the Core Programme. On December 2, 2004, during these scans, it was discovered the fastest millisecond pulsar ever known: it is the new source IGR J00291+5934, that has a pulsation period of 1.67 ms[22]. In December 2004, *INTEGRAL* was the first, of more than twenty satellites, to detect a gigantic flare from the soft $\gamma-$ray repeater SGR $1806-20$, so intense to significantly ionize the Earth's upper atmosphere[24,25,26].

The high angular resolution of *INTEGRAL* in the hard X-rays results crucial to disentangle the emission of different sources in crowded fields: for example, Paizis et al.[23] succeeded in studying GX $5-1$, that is apparently located close ($40'$) to the black hole GRS $1758-258$. Another case is represented by 4U $1630-47$, a black hole in the Norma Arm: Tomsick et al.[30] have shown that the extreme behaviour during the period $2002-2004$ is not in agreement with the classical definitions of spectral states.

Finally, among black holes, Cyg X-1 has been extensively studied during the Performance Verification phase, as it was the selected target for the first light of the main instruments[27,28,29].

### 2.3. *New sources and survey*

On January 29, 2003 *INTEGRAL* discovered its first new source[31], that was called IGR J$16318-4848$. It is located in the Norma Arm of the Galaxy, an active star forming region, where several other sources have been found later[b]. The high energy spectrum, from soft to hard X-rays as result of a joint observation of *XMM-Newton* and *INTEGRAL*, together with optical data, suggest that IGR J$16318-4848$ could be an accreting neutron star with a high-mass companion, enshrouded by a Compton-thick environment ($N_{\rm H}\approx 10^{24}$ cm$^{-2}$), perhaps the progenitor of a new population of X-ray binaries[32]. See also Kuulkers[33] for a recent review on this type of sources.

Recently, one of the new *INTEGRAL* sources, IGR J$18135-1751$, has been associated with an unidentified TeV source discovered by the HESS

[b]See the web page on the new *INTEGRAL* sources maintained by J. Rodriguez at `http://isdc.unige.ch/∼rodrigue/html/igrsources.html`

telescope[34], namely HESS J1813 − 178. The spectral energy distribution suggests that the object could be a pulsar wind nebula embedded in its supernova remnant[35]. Soon after, *INTEGRAL* discovered the soft $\gamma-$ray emission from another unidentified TeV source (HESS J1837 − 069), that appears to be another pulsar or supernova remnant[36].

Several other new sources have been discovered by *INTEGRAL* up to date: the first IBIS/ISGRI source catalog[37], referring to the data from February to October 2003, contains 123 known and 28 new sources down to a flux limit of $\approx 1.7\times10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the $20-100$ keV energy range (1 mCrab). The latest publicly available update back to a presentation by A. Bird[c] in January 2005 and reported 229 known and 31 new sources.

## 2.4. *Gamma-Ray Bursts (GRB)*

*INTEGRAL* has an elongated orbit with 72 hours period. This, in addition to the availability of the two ground stations of Redu and Goldstone, allows a continuous monitoring of the data in near-real time. This is performed by the *INTEGRAL Burst Alert System* (IBAS[38]), in order to distribute the GRB coordinates to the astronomical community with unprecedented coupling of high accuracy ($\approx 3'$) and low time delay ($\approx 20-30$ s). See Mereghetti & Götz[39] for a review of the IBAS activity. Among the several GRB detected by *INTEGRAL*, it is worth mentioning the first that was in the field of view of the instruments (IBIS, SPI). It occurred on November 25, 2002, during the Performance Verification phase[40,41]. Moreover, *INTEGRAL* detected also the GRB nearest to the Earth ($z = 0.106$)[42].

Other efficient ways to detect GRB (particularly out of the instruments FOV) are available on board *INTEGRAL* satellite with the Anticoincidence Shield (ACS) of SPI[43], the IBIS Compton mode (that makes use of both layers ISGRI and PICsIT)[44], and the spectral timing mode of IBIS/PICsIT[45]. In these ways, it is possible to reach energies up to a few MeV.

## 2.5. *Active Galactic Nuclei*

Although AGN are numerically much less than other sources detected by *INTEGRAL*, there are some interesting studies worth mentioning. Six blazars have been detected by *INTEGRAL* to date and it is worth noting that these are all also EGRET sources (i.e., that have been detected

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[c]Talk given at the *Internal INTEGRAL Science Workshop* held at ESA/ESTEC on 18 − 21 January 2005. See `http://integral.esac.esa.int/workshops/Jan2005/`.

at energies greater than 100 MeV by the EGRET experiment on board the *Compton Gamma-Ray Observatory*). Three of these six AGN have been detected during a multiwavelength Target-of-Opportunity (ToO) programme, led by E. Pian, organized to study the blazars in outburst. These are: S5 0716+714[46], following an outburst started at the end of March 2004; 3C 454.3[47], recently observed during the long outburst of May 2005; and S5 $0836+710$, serendipitously detected in the field of view of the observation of S5 $0716+714$[46]. The remaining three blazars are the well known 3C 273[48] and 3C 279[49] in the Virgo region, and PKS $1830-211$[50], the farthest object ($z = 2.51$) detected to date by *INTEGRAL*.

Still in the field of view of the ToO on S5 $0716+714$ are present two more AGN: the Seyfert active nuclei Markarian 3 and Markarian 6[46]. The data from Mkn 3 show a hint for the presence of a break in the spectrum between 60 and 100 keV, but the low statistics did not allow to better constrain the value[46].

Among the Seyferts, other studies have been done on NGC 4388[51], joint with *XMM-Newton*, and GRS $1734-292$[52], a luminous Seyfert 1 behind the Galactic Centre. This latter AGN is also the only source detected by *INTEGRAL* inside the 99% probability contours of the EGRET unidentified source 3EG $J1736-2908$ and thus opening the possibility that the AGN could be the counterpart of the EGRET source[53]. However, since no other Seyferts are known to emit at $E > 100$ MeV, if this association will be confirmed by future observations (with *GLAST*, for example) it remains to understand what is the physical mechanism able to generate high-energy $\gamma-$rays from a Seyfert active nucleus.

Other EGRET AGN observed by *INTEGRAL* are the radio galaxies NGC 6251[54] and Centaurus A[55]. In the former case, a faint doubtful detection was strengthened by the agreement of the measured flux with the spectral energy distribution expected from a synchrotron self-Compton model.

Several other AGN, together with a detection in the $30-50$ keV energy band of the Coma Cluster, are present in the field of view analyzed by Krivonos et al.[56]. This allowed to evaluate the extragalactic hard X-ray background as observed by *INTEGRAL*, but given the small sky area covered (3%), much larger samples are needed to better asses the source contribution in this energy band.

## 3. Final Remarks

Thanks to its main characteristics in the hard X/soft-$\gamma$ rays (high sensitivity, high angular resolution, high spectral resolution, wide FOV), at the end of the third year of operation *INTEGRAL* has significantly contributed to the advancement of the $\gamma-$ray astrophysics with several important contributions, a few of these have been shortly reviewed here. In addition, a public data archive is available to the astronomical community[d], where gigabytes of data are still waiting to be analyzed. We hope that this short review can be useful to show the huge work done to date, the work still to be done, and the potentialities of *INTEGRAL* in the exploration of the $\gamma-$ray sky.

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[d]Everything for the data analysis (data, software, documentation) can be found at the *INTEGRAL Science Data Centre* web page `http://isdc.unige.ch/`.

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